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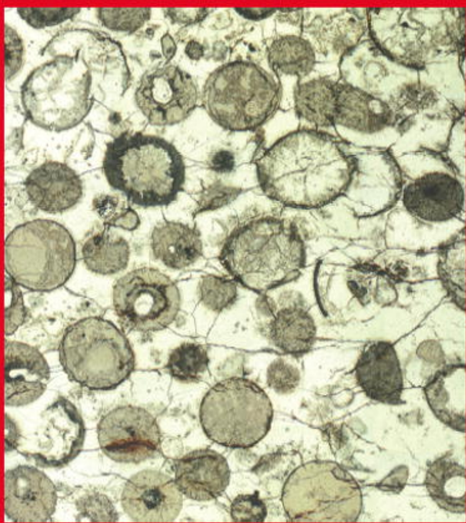

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Amalgamation between the Yangtze and Cathaysia Blocks in South China: Constraints from SHRIMP U–Pb zircon ages, geochemistry and Nd–Hf isotopes of the Shuangxiwu volcanic rocks

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ABSTRACT

South China was formed through the amalgamation of the Yangtze Block with the Cathaysia Block, but the timing of this amalgamation is controversial, ranging from Mesoproterozoic to Mesozoic. We report here SHRIMP U–Pb zircon ages, geochemistry and Nd–Hf isotopes of the Shuangxiwu Group volcanic rocks from the southeastern Yangtze Block. These rocks were strongly deformed, metamorphosed to greenschist-facies, intruded by 849 ± 7 Ma dolerites, and unconformably overlain by Neoproterozoic rift successions of no older than ca. 820 Ma. The Beiwu and Zhangcun volcanic rocks from the middle and uppermost Shuangxiwu Group were dated at 926 ± 15 Ma and 891 ± 12 Ma, respectively. All the studied rocks are characterized by highly positive εNd(T) (5.4–8.7) and εHf(T) (11.0–15.3) values. The Pingshui basaltic and andesitic rocks from the lower Shuangxiwu Group, which were previously dated at ca. 970 Ma, are high in Al_2O_3 (15–20%) but low in MgO (<8%), and are characterized by enrichments in Th and LREE but depletions in Nb, Ta, Zr, Hf and Ti, broadly similar to high-Al basaltic rocks in many volcanic arcs. The Beiwu andesitic to rhyolitic rocks have higher MgO than the experimental melts of basaltic rocks, and their Al_2O_3 content decreases with increasing SiO_2, similar to the regional coeval tonalites and granodiorites, suggesting their formation by crystal fractionation of basaltic parent magma. The Zhangcun volcanic rocks are high in SiO_2 (mostly >69%), low in MgO (0.35–1.2%), and have nearly constant Al_2O_3 contents of 14–15% and relatively uniform trace element concentrations. They were generated by remelting of juvenile mafic to intermediate arc rocks. Overall, the Shuangxiwu Group volcanic rocks and associated intrusive tonalites and granodiorites constitute a typical calc-alkaline magmatic assemblage of a 970–890 Ma active continental margin. These results and the 849 ± 7 Ma zircon U–Pb age for the undeformed doleritic dikes intruding the Shuangxiwu Group suggest that the tectonic regime of the study region transformed from plate convergence to intracontinental rifting in the time period between ca. 890 Ma and ca. 850 Ma. Previously reported 1.04–0.94 Ga metamorphic and deformation ages from the nearby Tianli Schists and evidence for the final closure of the back-arc basin at ca. 880 Ma (ophilitic obduction at Xiwan), further suggest that the amalgamation between the Yangtze and Cathaysia Blocks, likely through "soft docking" at the eastern segment of the Sibao orogen, was completed at ca. 880 Ma or soon after.

1. Introduction

It is widely accepted that the South China Block was formed through the amalgamation of the Yangtze Block with the Cathaysia Block, but the timing of the amalgamation has been a topic of debate. A number of studies in the late 1980s suggested that this occurred through a collisional orogenesis in South China during the early Mesozoic (Hsü et al., 1988, 1990) or early Paleozoic (Haynes, 1988). Because of the lack of geological evidence, such models were

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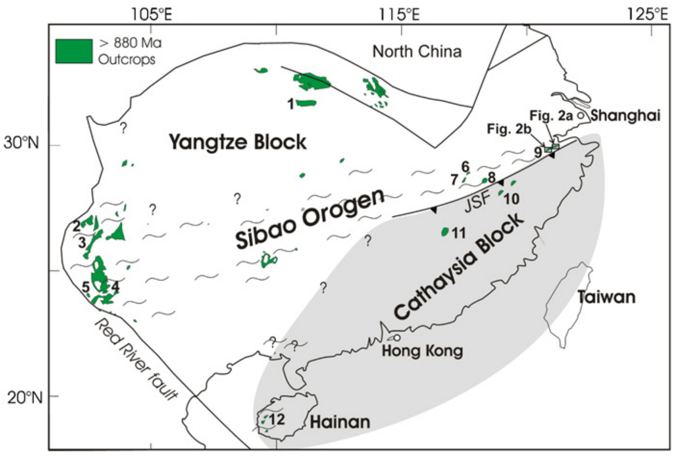

Fig. 1. Distribution of the Sibao orogen and major pre-880 Ma outcrops in South China (modified after Z.X. Li et al., 2007). Sources of information: 1: the Archean Kongling complex forming the oldest Yangtze basement (Gao et al., 1999; Qiu et al., 2000); 2: the tightly folded ca. 0.92 Ga Yanbian Group (Zhou et al., 2006; X.H. Li et al., 2006a); 3: the ca. 1.0 Ga Huiqinggou granitic gneiss and 1.0 Ga foreland-basin deposits (Z.X. Li et al., 2002); 4: the ca. 1.14–0.96 Ga Laowushan Formation and Kunyang foreland-basin deposits (Greentree et al., 2006); 5: the ca. 1.7 Ga Dahongshan Group (Hu et al., 1991; Greentree and Li, 2008); 6: the ca. 0.97 Ga Xiwan adakitic granite (X.H. Li et al., 1994; Li and Li, 2003); 7: the ca. 1.0 Ga Zhangshudun ultramafic complex within the NE Jiangxi Ophiolite (Chen et al., 1991); 8: the Tianli Schists that were deposited after 1.5 Ga and metamorphosed at 1.04–0.94 Ga (Z.X. Li et al., 2007); 9: the ca. 0.97–0.89 Ga Shuangxiwu arc (Ye et al., 2007; this study), with enlarged maps shown in Fig. 2; 10: the 1.83 Ga Danzhu gneissic granite (Li and Li, 2007); 11: the ca. 1.77 Ga Tianjingping amphibolite (Li, 1997); and 12: the Baoban complex that was intruded by ca. 1.43 Ga granites and metamorphosed at 1.3–1.0 Ga (Z.X. Li et al., 2002). JSF: Jiangshan-Shaoxing Fault.

challenged by subsequent studies (e.g., Chen et al., 1991; Charvet et al., 1996a,b; Li and McCulloch, 1996). Most researchers now believe that the two blocks amalgamated during the Proterozoic Sibao orogeny (also called the "Jiangnan" or "Jinning" orogeny by different authors in the literature), but the timing and evolution of the orogeny are still controversial. Some researchers suggested that the Sibao orogen belongs to part of the worldwide Grenvillian-aged orogenic events associated with the assembly of Rodinia (e.g., Z.X. Li et al., 1995, 2002, 2007, 2008; Greentree et al., 2006; X.H. Li et al., 2006a; Ye et al., 2007; W.X. Li et al., 2008a), whereas others considered that the Sibao orogeny lasted until ca. 0.82 Ga or even younger (e.g., Li, 1999; Zhao and Cawood, 1999; Zhou et al., 2002, 2004; X.L. Wang et al., 2004, 2006, 2007, 2008; Wu et al., 2006; Zheng et al., 2007).

Located at the southeastern margin of the Yangtze Block (Fig. 1), the Shuagxiwu anticline (Fig. 2b) consists of a suite of greenschist-facies, strongly deformed volcanic rocks overlain with an angular unconformity by middle Neoproterozoic rift volcano-sedimentary sequences. In this paper, we report SHRIMP U–Pb zircon ages and geochemical and Nd–Hf isotopic data for the Shuangxiwu calc-alkaline volcanic rocks. We demonstrate that the Shuangxiwu volcanic rocks represent an assemblage of arc volcanism formed on the eastern segment of the Sibao orogen at ca. 0.97–0.89 Ga, broadly coeval with regional metamorphism and deformation related to the Sibao orogeny (Z.X. Li et al., 2007) prior to the final amalgamation between the Yangtze and Cathaysia Blocks.

2. Geological background

The South China Block consists of the Yangtze Block and the Cathaysia Block, separated by the Sibao orogen (Fig. 1). Outcrops of pre-Neoproterozoic crystalline basement rocks are scarce in the Yangtze Block, with the oldest being the Kongling complex near the Yangtze Gorge Dam (marked as "1" in Fig. 1) consisting of Archean to Paleoproterozoic high-grade metamorphic TTG (tonalite, trondhjemite and granodiorite) gneisses, metasedimentary rocks and amphibolites (e.g., Gao et al., 1999; Qiu et al., 2000). Variably deformed, low- to medium-grade metamorphic rocks of late Paleoproterozoic to early Neoproterozoic (≥900 Ma) ages are sporadically distributed around the margins of the Yangtze Block (Fig. 1). Some of them are well-dated, including, from west to east, the ca. 1.7 Ga Dahongshan Group in western Yunnan (Hu et al., 1991; Greentree and Li, 2008; "5" in Fig. 1), the 1.0 Ga Huiqinggou granitic gneiss (Z.X. Li et al., 2002; "3" in Fig. 1) and the 1.0–0.9 Ga Kunyang and Yanbian Groups and equivalents in western Yunnan and southern Sichuan (Greentree et al., 2006; X.H. Li et al., 2006a; "2" and "4" in Fig. 1), the Mesoproterozoic Tianli Schists (Z.X. Li et al., 2007; "8" in Fig. 1), the ca. 1.0 Ga ophiolites and the ca. 970 Ma Xiwan adakitic rocks in northeastern Jiangxi (Chen et al., 1991; Li and Li, 2003; "6" and "7" in Fig. 1), and the ca. 910 Ma Taohong and Xiqiu tonalite and granodiorite plutons in northeastern Zhejiang that intrude the Pingshui Formation of the lowest Shuangxiwu group (Ye et al., 2007; "9" in Fig. 1). The Jiangshan-

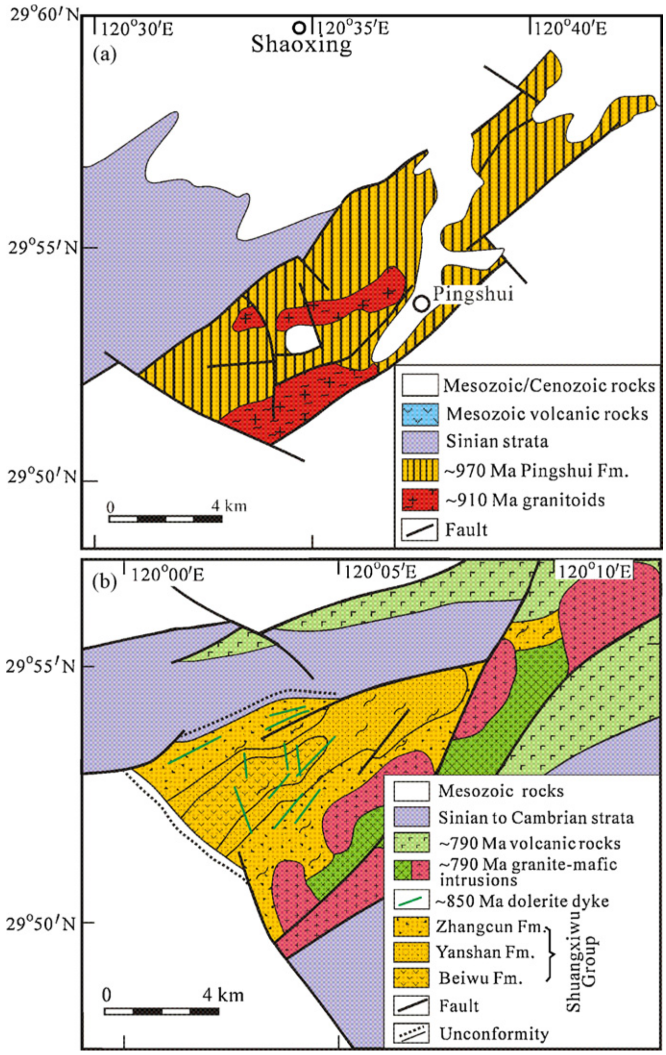

Fig. 2. Geological map of (a) the Pingshui area showing the distribution of the Pingshui Formation, the lower most unit of the Shuangxiwu Group, and (b) the Shuangxiwu area showing the Baiwu, Yanshan and Zhangcun Formations of the middle, upper and uppermost Shuangxiwu Group (simplified after the 1:200,000 geological map (ZPGST, 1975)). Ages for the ca. 970 Ma Pingshui Formation are from Zhang et al. (1990) and Chen et al. (2009); the ca. 910 Ma granitoids from Ye et al. (2007); the ca. 850 Ma dolerite dyke and ca. 790 Ma volcanic and granite-mafic intrusions from Z.X. Li et al. (2003) and X.H. Li et al. (2008).

Shaoxing Fault ("JSF" in Fig. 1) is considered a major boundary between the Yangtze and Cathaysia Blocks (Zhang et al., 2005), possibly partially truncating the eastern segment of the Sibao orogen during its Phanerozoic activations (Fig. 1).

The protolith of the Tianli Schists was a clastic sedimentary succession deposited sometime between 1.5 and 1.04 Ga (Z.X. Li et al., 2007). It underwent two major episodes of deformation and metamorphism to upper greenschist-facies, at ca. 1.04–1.02 Ga and ca. 0.97–0.94 Ga, respectively, during the Sibao orogeny (Z.X. Li et al., 2007).

The Shuangxiwu Group consists predominantly of volcanic and pyroclastic rocks interbedded with felsic tuff and tuffaceous sandstones and siltstones that were strongly deformed and metamorphosed to greenschist-facies. It was divided into four formations according to lithologic characteristics, including, from bottom to top, the Pingshui, Beiwu, Yanshan and Zhangcun Formations (BGMRZJ, 1989). The Pingshui Formation, exposed around Pingshui (Fig. 2a), consists chiefly of altered basaltic to andesitic rocks. It is regarded as the lowest formation in the group, although it has no direct contact with the other three formations. The minimum age of the Pingshui Formation is constrained by the SHRIMP zircon U–Pb age of 913 ± 15 Ma for the Taohong pluton that intrudes the Pingshui basalts (Ye et al., 2007). Chen et al. (2009) recently reported LA-ICPMS U–Pb zircon analyses for two volcanic rocks from the Pingshui Formation. While the average $^{206}Pb/^{238}Pb$ ages of 904 ± 8 Ma and 906 ± 10 Ma were interpreted by the authors as the formation age of the Pingshui volcanic rocks, it is noted that their measured U–Pb data are highly discordant, with $^{206}Pb/^{238}Pb$ ages ranging from 878 to 999 Ma. On the other hand, the two dated samples have nearly identical $^{207}Pb/^{206}Pb$ ages within errors, with a mean of 965 ± 12 Ma. This Pb/Pb age, consistent with the Sm–Nd internal isochron age of 978 ± 44 Ma (Zhang et al., 1990), can be considered as the best estimate of the formation age of the Pingshui volcanic rocks.

The other three formations crop out in the Shuangxiwu anticline, ca. 50 km to the west of Pingshui, consisting of intermediate to felsic volcanic and volcaniclastic rocks with a total thickness of >1800 m (Fig. 2b). The lowermost Beiwu Formation, with a thickness of ca. 430 m, consists of andesite, dacite and rhyolite as well as volcaniclastic interbeds. Conformably overlying the Beiwu Formation is the Yanshan Formation, which consists mainly of felsic tuff, tuffaceous sandstones and siltstones with a thickness of ca. 470 m. At the top of the Shuangxiwu Group is the Zhangcun Formation that consists chiefly of felsic ignimbrite with a thickness of ca. 850 m. The Zhangcun Formation is unconformably overlain by basal conglomerates and bimodal volcanic rocks of the ~800 Ma rift successions (Z.X. Li et al., 2003; X.H. Li et al., 2008). Precise isotopic age has been lacking for the Shuangxiwu volcanic rocks except for a zircon evaporation Pb–Pb date of ca. 900 Ma for the uppermost Zhangcun rhyolite (Cheng, 1993). The minimum age of the Shuangxuwu volcanic rocks is constrained by the SHRIMP zircon U–Pb ages of 849 ± 7 Ma for the Shenwu dolerites that intrude the volcanic rocks (X.H. Li et al., 2008).

3. Analytical procedures

3.1. SHRIMP U–Pb zircon dating

Zircon concentrates were separated from ca. 5-kg samples using standard density and magnetic separation techniques. Zircon grains, together with zircon standard TEMORA (for sample 04ZJ67) and CZ3 (for sample 97Zh6), were mounted in epoxy mounts which were then polished to section the crystals in half for analysis. All zircons were documented with photomicrographs and cathodoluminescence (CL) images to reveal their internal structures. Measurements of U, Th, and Pb for sample 04ZJ67 were conducted using the SHRIMP II ion microprobe at the Beijing SHRIMP Center, Chinese Academy of Geological Sciences. U–Th–Pb ratios were determined relative to the TEMORA standard zircon (Black et al., 2004), and the absolute abundances were calibrated to the standard zircon SL13 (U = 238 ppm). Sample 97Zh6 was analyzed using the SHRIMP II(A) ion microprobe at Curtin University of Technology, with U–Th–Pb isotopic ratios and abundances being determined relative to the CZ3 standard (Nelson, 1997). Analyses of the standard zircons were interspersed with those of unknown grains. Measured compositions were corrected for common Pb using the measured ^{204}Pb, and an average crustal composition (Cumming and Richards, 1975) appropriate to the age of the mineral was assumed. Because the common Pb is very low, the common Pb corrections were insensitive to the choice of common Pb compositions. U–Pb zircon data are listed in Table 1 (Appendix A). Uncertainties on individual analyses are reported at the 1σ level; mean ages for pooled $^{206}Pb/^{238}U$ results are quoted at the 95% confidence level.

3.2. Major and trace elements

After petrographic examination, the least-altered whole-rock samples were selected for geochemical and Nd–Hf isotopic analyses. Major element oxides were analyzed using a Rigaku RIX 2000 X-ray fluorescence spectrometer at the Guangzhou Institute of Geochemistry on fused glass beads. Calibration lines used in quantification were produced by bivariate regression of data from 36 reference materials encompassing a wide range of silicate compositions (X.H. Li et al., 2005), and analytical uncertainties are between 1% and 5%. Trace elements were analyzed using a PerkinElmer Sciex ELAN 6000 inductively coupled plasma mass spectrometer (ICP-MS) at the Guangzhou Institute of Geochemistry. Analytical procedures are similar to those described by X.H. Li et al. (2000). About 50 mg of each powdered sample was dissolved in a high-pressure Teflon bomb for 24 h using a $HF + HNO_3$ mixture. An internal standard solution containing the single element Rh was used to monitor signal drift during counting. A set of USGS and Chinese national rock standards including BHVO-1, W-2, AGV-1, G-2, GSR-1 and GSR-3 were chosen for calibrating element concentrations of unknowns, and analytical precision is typically 2–5%. Geochemical results are listed in Table 2 (Appendix A).

3.3. Whole-rock Nd–Hf isotopic compositions

Nd isotopic compositions were determined using a Micromass Isoprobe multi-collector ICP-MS at the Guangzhou Institute of Geochemistry, using analytical procedures described by X.H. Li et al. (2004). Nd fractions were separated by passing through cation columns followed by HDEHP columns. Measured $^{143}Nd/^{144}Nd$ ratios were normalized to $^{146}Nd/^{144}Nd = 0.7219$, and the reported $^{143}Nd/^{144}Nd$ ratios were further adjusted relative to the Shin Etsu JNdi-1 standard of 0.512115. Separation of Hf from the matrix and rare earth elements was carried out using a combination of Eichrom RE and HDEHP columns. Hf isotopic compositions were determined using a Finnigan Neptune MC-ICP-MS at the Institute of Geology and Geophysics, using analytical procedures described by X.H. Li et al. (2007). The measured $^{176}Hf/^{177}Hf$ ratios were normalized to $^{179}Hf/^{177}Hf = 0.7325$, and the reported $^{176}Hf/^{177}Hf$ ratios were further adjusted relative to the JMC 475 standard of 0.282160 (Nowell et al., 1998). Whole-rock Nd and Hf isotopic data are listed in Table 3 (Appendix A).

4. Results

4.1. U–Pb zircon ages

Sample 04ZJ67 is a rhyolite collected from the Beiwu Formation (29°52′19″N, 120°02′35″E). Zircons are mostly euhedral to subhedral, transparent and colorless, ranging from 50 μm to 150 μm in length, and have length to width ratios between 2:1 and 3:1. Euhedral concentric zoning is common in most crystals in CL. Sixteen analyses of 16 zircons were obtained in sets of five scans during a single analytical session (Table 1, Appendix A). Th concentrations range from 4 ppm to 422 ppm, U from 70 to 3128 ppm, and Th/U ratios from 0.01 to 1.43. Common Pb is low; the proportions of common ^{206}Pb in total measured ^{206}Pb (f_{206} in Table 1, Appendix A) are mostly <0.5%. The measured $^{206}Pb/^{238}U$ ages vary from 227 Ma to 2330 Ma (Fig. 3a). Among them, two oval crystals (spots 4 and 5), display significantly old and discordant U–Pb results, with $^{207}Pb/^{206}Pb$ ages of 1935 ± 26 Ma (1σ) and 2543 ± 10 Ma (1σ), respectively. They are thus interpreted as xenocrysts. The dominant age population consists of eight analyses (spots 1, 2, 6, 7, 13, 14, 15 and 16) that have concordant U–Pb isotopic compositions with a weighted mean of $^{206}Pb/^{238}U$ age of 926 ± 15 Ma. This age is interpreted as the best estimate of the crystallization age for sample 04ZJ67. Spot 12 yields a slightly younger, discordant U–Pb age likely due to partial loss of radiogenic Pb. The remaining five analyses (spots 3, 8, 9, 10 and 11) are discordant, with $^{206}Pb/^{238}U$ age ranging from 227 to 289 Ma (Table 1, Appendix A). These zircons are relatively small and characterized by low Th/U ratios between 0.01 and 0.10, interpreted as metamorphic in origin. Apart from the two xenocrysts (spots 4 and 5), all other spots define a discordia with upper and lower intercepts at 952 ± 38 Ma and 246 ± 11 Ma, respectively (Fig. 3a). The latter is interpreted as the best estimate of the timing of metamorphism, comparable with the timing of the regional Indosinian orogenic magmatism and metamorphism (e.g. X.H. Li et al., 2006b; Li and Li, 2007).

Sample 97Zh6 is a rhyolite collected from the uppermost Zhangcun Formation (29°51′40″N, 120°04′45″E). The zircons were mostly euhedral to subhedral, 100–150 μm in length with length to width ratios of about 2:1. Most zircons are transparent and colorless, with weak euhedral concentric zoning visible in CL. Eight analyses of 8 zircons were obtained (Table 1, Appendix A). These zircon grains have relatively low concentrations of U (73–232 ppm) and Th (24–224 ppm); Th/U ratio ranges from 0.33 to 0.97. All the analyses have indistinguishable U–Pb isotopic compositions within errors, which correspond to a single age population with a concordia $^{206}Pb/^{238}U$ age of 891 ± 12 Ma (Fig. 3b). This age is consistent with a previously reported zircon evaporation Pb–Pb date of ca. 900 Ma (Cheng, 1993), and is interpreted as the eruption age of the Zhangcun volcanic rocks.

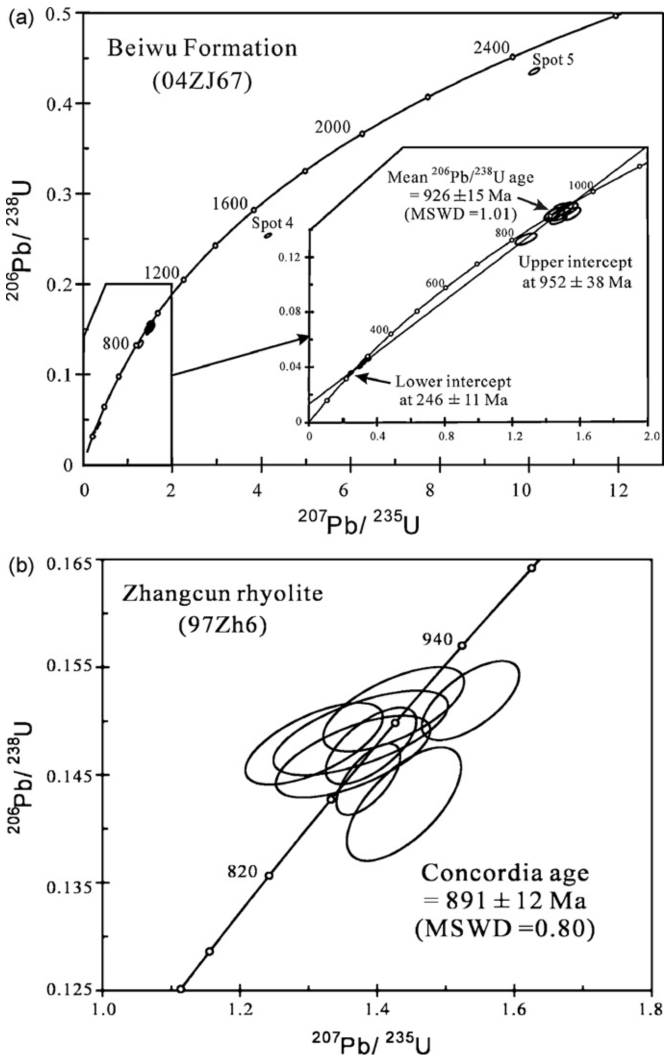

Fig. 3. U–Pb zircon concordia diagram for (a) rhyolite sample 04ZJ67 from the Baiwu Formation of the middle Shuangxiwu Group, and (b) rhyolite sample 97Zh6 from the Zhangcun Formation from the uppermost Shuangxiwu Group.

4.2. Effects of alteration and metamorphism on chemical compositions

The studied volcanic rocks underwent greenschist-facies metamorphism and varying degrees of alteration. Their LOI (loss of ignition) values are highly variable, ranging from 4.2 to 8.0% for the Pingshui Formation rocks, 1.1 to 4.5% for the Beiwu Foramtion rocks, and 1.1 to 2.4% for the Zhangcun Formation rocks (Table 2, Appendix A). In general, the mafic rocks have higher LOI values than the felsic rocks. Thus, the effects of metamorphism and alteration on chemical compositions of these rocks need to be evaluated prior to any investigation of their geochemical characters. Zirconium in igneous rocks is generally considered to be the most immobile during low- to medium-grade metamorphism and alteration except for severe seafloor-hydrothermal alteration (e.g., Wood et al., 1979; Gibson et al., 1982). Fig. 4 shows the different geochemical behaviors of a number of elements against Zr contents.

The Zhangcun Formation rocks have the lowest LOI values and their major and trace elements show consistent variations with Zr, suggesting insignificant metamorphic and alteration effects on their geochemical composition. For rocks from the Pingshui and Beiwu Formations, alkaline (such as Rb) and alkaline earth (such as Sr) elements are overall scattered, implying varying degrees of mobility, whereas other elements are generally correlated with Zr, indicating that these elements are essentially immobile during metamorphism and alteration. In the following sections, only the immobile elements are used for rock classification and in petrogenetic discussions.

4.3. Geochemical characteristics

The Shuangxiwu volcanic rocks have a wide range of SiO_2 contents (between 53 and 74%). Most of the older, ca. 970 Ma rocks from the Pingshui Formation are basaltic to andesitic in composition (SiO_2 = 53–59%), whereas the younger, ca. 930–890 Ma rocks from the Beiwu and Zhangcun Formations are mainly andesitic to rhyolitic (SiO_2 = 57–74%). On the SiO_2 vs. Zr/TiO_2 diagram of Winchester and Floyd (1976), all the volcanic rocks plot into the sub-alkaline field (Fig. 5). Major elements (apart from K_2O and Na_2O) show con-

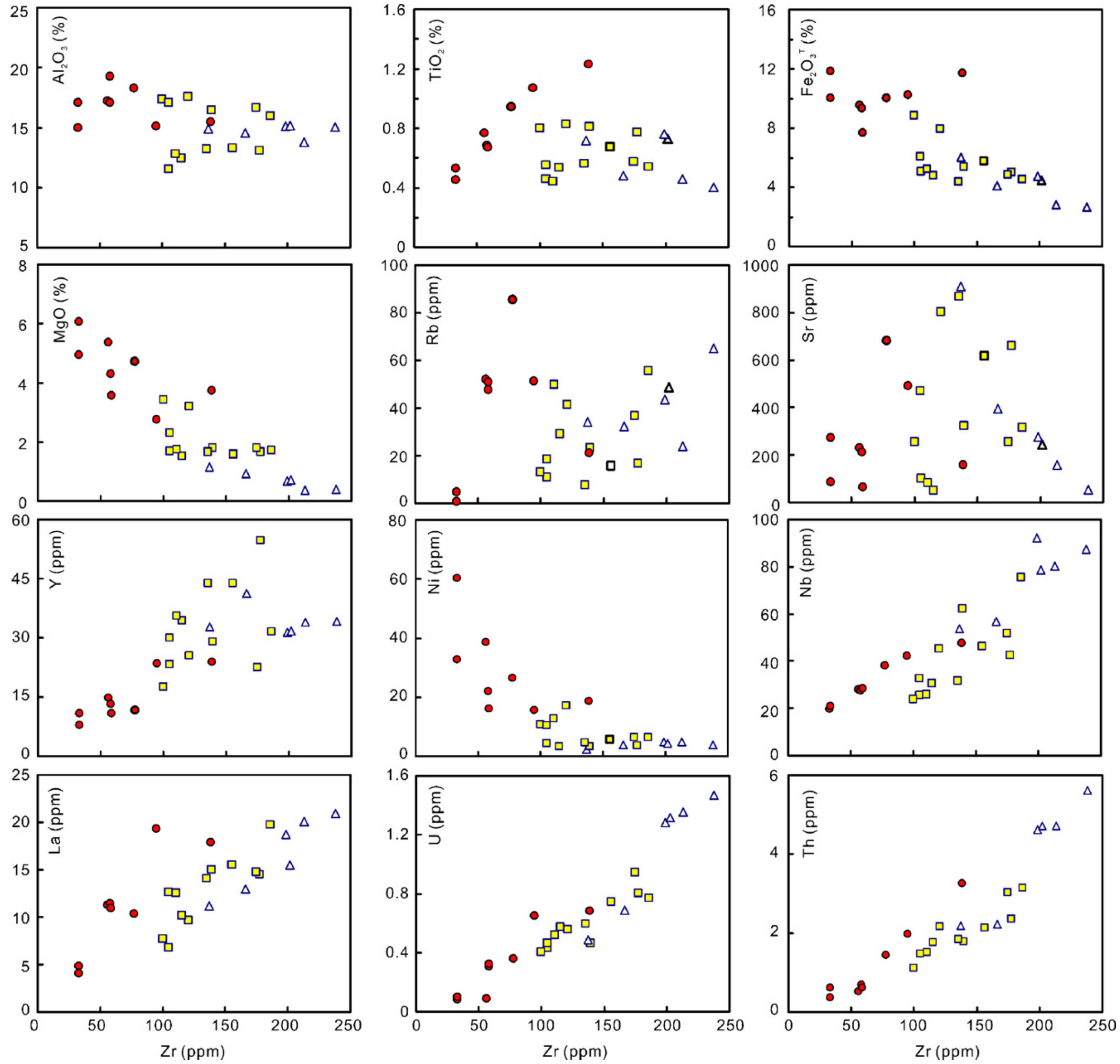

Fig. 4. Plots of selected major and trace elements vs. Zr to evaluate the mobility of these elements during alteration. Red circle: Pingshui Formation rocks; yellow square: Beiwu Formation rocks; blue triangle: Zhangcun Formation rocks. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

sistent variations in Harker diagrams (Fig. 6). The Pingshui basaltic to andesitic rocks show decreases in Al_2O_3, MgO, $Fe_2O_3^T$ and CaO with increasing SiO_2, whereas TiO_2 and P_2O_5 increase until SiO_2 reaches ~58% and then decrease at higher SiO_2 contents. The Beiwu and Zhangcun felsic rocks display decreases in all these major elements with increasing SiO_2.

The chondrite-normalized REE patterns are illustrated in Fig. 7. All the rocks show moderate LREE-enriched patterns, and their total REE content increases with increasing SiO_2. The Pingshui basaltic and andesitic rocks and the Beiwu andesitic rocks have weak Eu anomalies, whereas the Beiwu and Zhangcun felsic rocks show distinct Eu anomalies (Eu/Eu* = 0.62–0.85). The Zhangcun felsic rocks have the most consistent REE abundances and patterns. In the primitive mantle-normalized spidergrams (Fig. 7d–f), all the volcanic rocks from the Shuangxiwu Group show "spiky" trace element patterns, with enrichment in Th and LREE and variable depletion in Nb, Ta, P, Ti, and to a lesser extent Eu. It is noteworthy that the basaltic and andesitic rocks from the Pingshui and the Beiwu Formations display strong Zr and Hf depletion relative to Nd and Sm, whereas such depletion is not shown in the felsic rocks from the Beiwu and Zhangcun Formations.

4.4. Nd–Hf isotopes

Despite variable chemical compositions (from basaltic andesite to rhyolite) and wide ranges of measured $^{147}Sm/^{144}Nd$ (0.121–0.187) and $^{176}Lu/^{177}Hf$ (0.0094–0.0421) ratios, all the studied volcanic rocks have fairly constant initial Nd and Hf isotopic compositions, with $\varepsilon Nd(T) = 5.4–8.7$ and $\varepsilon Hf(T) = 11.0–15.3$, broadly similar to the Nd and Hf isotopic compositions of the associated Xiqiu and Taohong tonalite and granodiorite intrusions (Table 3, Appendix A). These rocks have Nd and Hf model ages mostly between 0.9 and 1.1 Ga, that are fairly close to their formation ages (Table 3, Appendix A). On the Hf–Nd isotopic plot

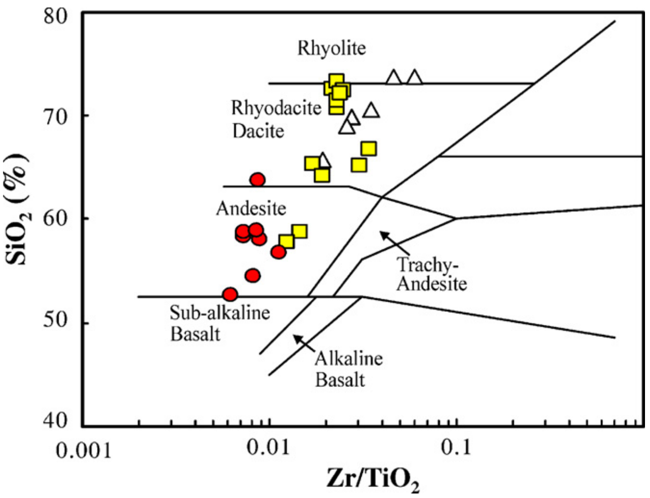

Fig. 5. SiO_2 vs. Zr/TiO_2 classification diagram of Winchester and Floyd (1976) Symbols are same as in Fig. 4.

(Fig. 8), their εHf and εNd values fall within the "Terrestrial Array" (Vervoort et al., 1999) between MORB and OIB, indicating that these rocks were derived predominantly from time-integrated depleted sources, and contributions from ancient continental crust played very little, if any, role in their origin.

5. Discussions

5.1. Petrogenesis

The Pingshui basaltic rocks are high in Al_2O_3 (15–20%), but low in MgO (<8%), and are characterized by enrichment of Th and LREE but depletion in high field strength elements (HFSE). They show pronounced negative Nb–Ta, Zr–Hf and Ti anomalies relative to the neighboring elements in the incompatible trace element spidergram (Fig. 7d) similar to those of arc basalts (McCulloch and Gamble, 1991; Tatsumi and Eggins, 1995). Although depletion in Nb, Ta and Ti can also be observed in some intraplate basalts due to either interaction with subcontinental lithospheric mantle or crustal contamination (Ellam and Cox, 1991; Hawkesworth et al., 1995; X.C. Wang et al., 2008), significant depletion in Zr and Hf relative to Nd and Sm is characteristic of basalts derived from mantle wedge metasomatized by subduction-related fluids (Fig. 9), as Zr and Hf typically display low solubility in fluids whereas they can show significant mobility in slab melts (e.g., La Flèche et al., 1998; Münker et al., 2004).

On the Zr–Ti discrimination diagram of Pearce (1982), the Pingshui basaltic rocks fall into the island-arc field (Fig. 10a), and are distinctive from the within-plate basalts. They are low in TiO_2 (0.5–1.2%) and have low Ti/V ratios (10–24), plotting in the arc basalts field on the Ti–V discrimination diagram of Shervais (1982) (Fig. 10b). The Pingshui basaltic rocks have characteristically low Mg# (<0.6), are low in Cr (<150 ppm) and Ni (<110 ppm), and have high εNd(T) and εHf(T) values, suggesting that they have undergone intensive olivine and clinopyroxene fractionation without appreciable involvement of continental crustal components. Insignificant to positive Eu anomalies (Fig. 7a) are consistent with a considerable delay of plagioclase crystallization to form high-alumina differentiates under high partial pressure of H_2O (e.g., Sisson and Grove, 1993; Schiano et al., 2004). Overall, the Pingshui basaltic rocks are similar in geochemistry to the high-Al basaltic rocks which are the most common rock type in many volcanic arcs (e.g., Crawford et al., 1987).

The Beiwu rocks are andesite to rhyolite in composition (SiO_2 = 57.8–73.4%), whereas the Zhangcun samples are dacite and rhyolite in composition (SiO_2 = 65.8–73.7%). They are mostly metaluminous to weakly peraluminous, with A/CNK [molar Al/(Ca + Na + K)] = 0.75–1.1. A few samples have anomalously high A/CNK value of ~1.3 possible due to mobility of alkaline elements during alteration. All the samples are characterized by depleted mantle-like Nd and Hf isotopic compositions (εNd(T) > 5.5 and εHf(T) > 11), indicating inappreciable involvement of ancient continental components. All these geochemical and isotopic features suggest that these calc-alkaline, intermediate to felsic volcanic rocks are products of either fractional crystallization of mantle-derived calc-alkaline basaltic magma (e.g., Singer et al., 1992; Barth

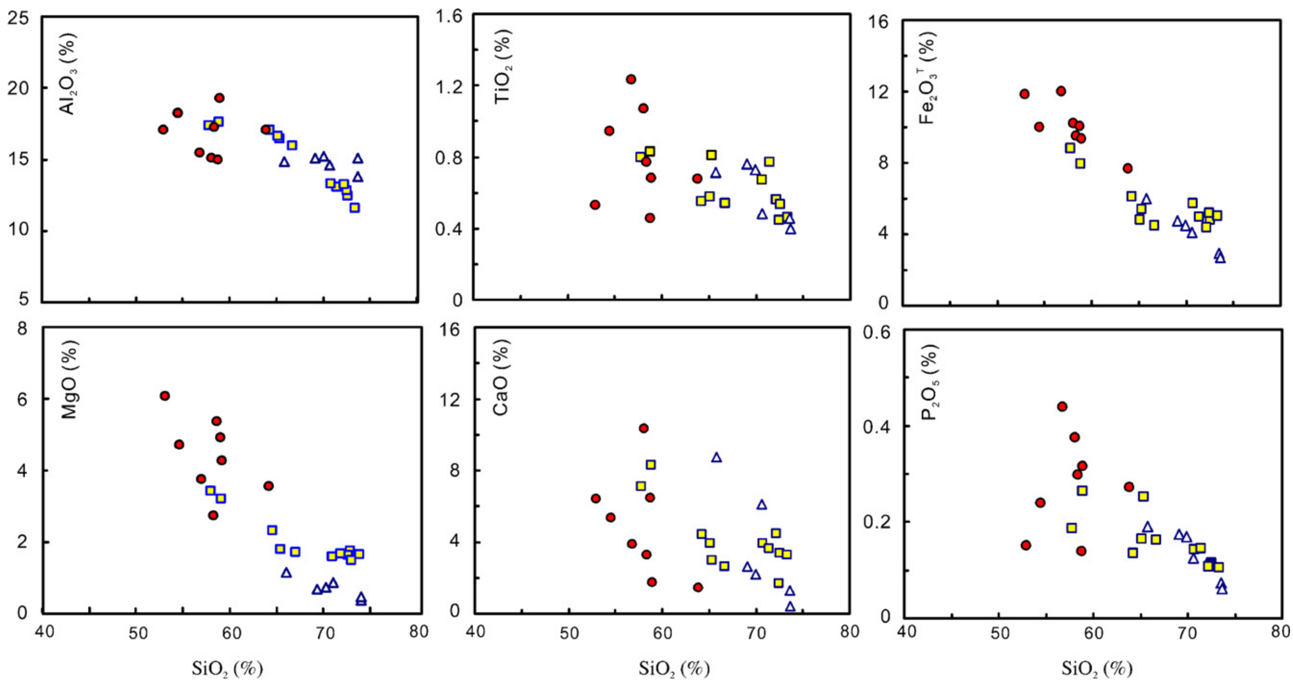

Fig. 6. Chemical variation Harker diagrams for the Shuangxiwu volcanic rocks. Symbols are same as in Fig. 4.

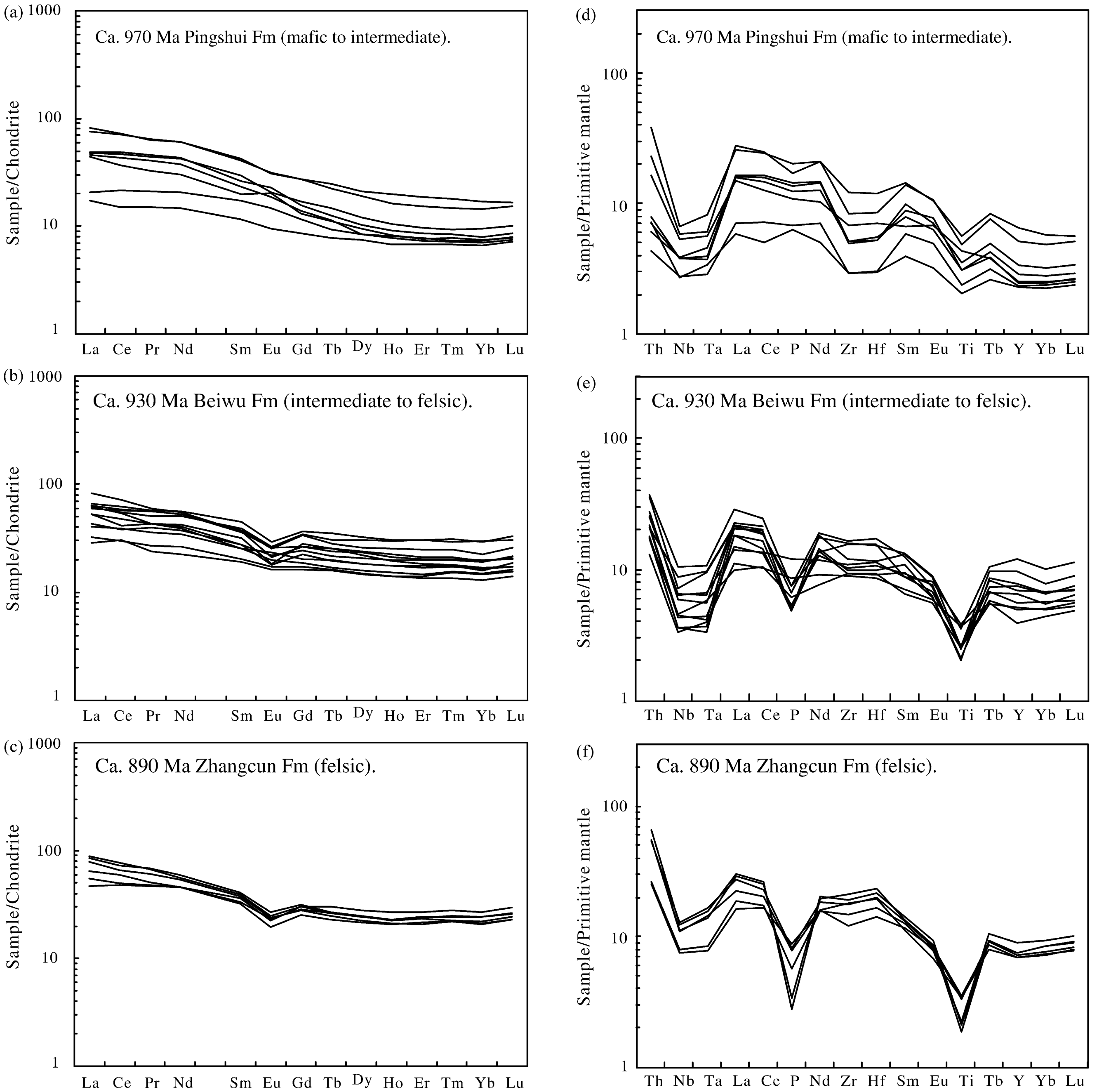

Fig. 7. (a–f) Chondrite-normalized REE diagrams and primitive mantle-normalized incompatible element spidergrams for the Shuangxiwu volcanic rocks. The normalization values are from Sun and McDonough (1989).

et al., 1995), or partial melting of juvenile sub-alkaline metabasaltic rocks (e.g., Drummond and Defant, 1990; Rushmer, 1991; Rapp and Watson, 1995). Despite similarities in Nd and Hf isotopic compositions, the Beiwu and Zhangcun rocks display distinct major element variation trends. At a given SiO_2 content, the Beiwu samples have overall higher MgO and lower Al_2O_3 contents than the Zhangcun samples (Fig. 6). Fig. 11 is a plot of MgO vs. SiO_2 showing the experimental liquids obtained by melting of basaltic protoliths. At a given SiO_2 content, the Beiwu rocks have MgO concentrations clearly higher than the experimental melts. Therefore, these rocks were unlikely to have been generated by melting of metabasaltic rocks. Although the Beiwu volcanic rocks have MgO concentrations similar to that of modern adakites produced by melting of subducted oceanic crust through interactions with the mantle (e.g. Drummond and Defant, 1990; Smithies, 2000), they are significantly lower in Sr/Y (1.4–31.6) but higher in Y (18–55 ppm) and HREE (such as Yb = 2.5–5.1 ppm) than typical adakites (e.g., Defant and Drummond, 1993). Hence, they are different in origin from adakites. Two andesitic samples from the Beiwu Formation show Zr and Hf depletion relative to Sm (Fig. 7e), similar to the Pingshui basaltic to andesitic rocks. In general, the Beiwu volcanic rocks are very similar in geochemistry and Nd–Hf isotopes to the coeval Taohong and Xiqiu tonalite and granodiorite (Fig. 8) in the study area that were thought to be formed by crystal fractionation of basaltic magmas (Ye et al., 2007). All these features suggest that the Beiwu andesitic to rhyolitic rocks are likely formed by crystal fractionation of basaltic magmas. A distinct Eu negative anomaly and a sharp decrease of Al_2O_3 with increasing SiO_2 indicate that plagioclase was a predominant fractional phase.

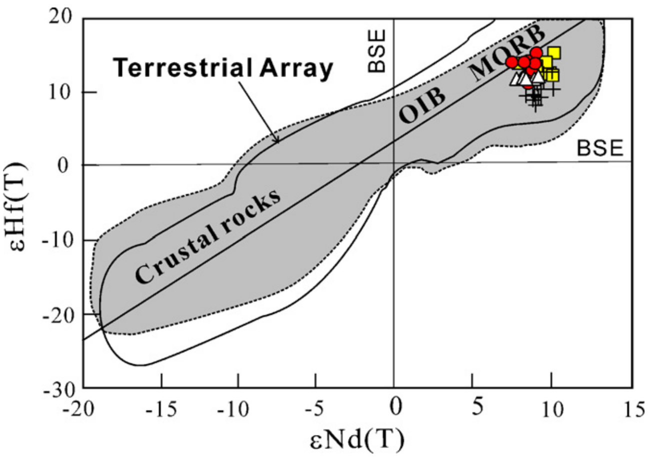

Fig. 8. Plot of εHf(T) vs. εNd(T) values for the Shuangxiwu volcanic rocks and the ca. 910 Ma tonalites and granodiorites that intruded the Pingshui Formation. "Terrestrial Array" indicates the Hf–Nd isotopic variation of present-day OIB, MORB and crustal clastic sediments and felsic igneous rocks (Vervoort et al., 1999); Grey area shows the time-corrected "Terrestrial Array" at ca. 0.9 Ga. BSE: bulk silicate Earth; black crosses: the Xiqiu and Taohong tonalite and granodiorite intrusions; other symbols are same as in Fig. 4.

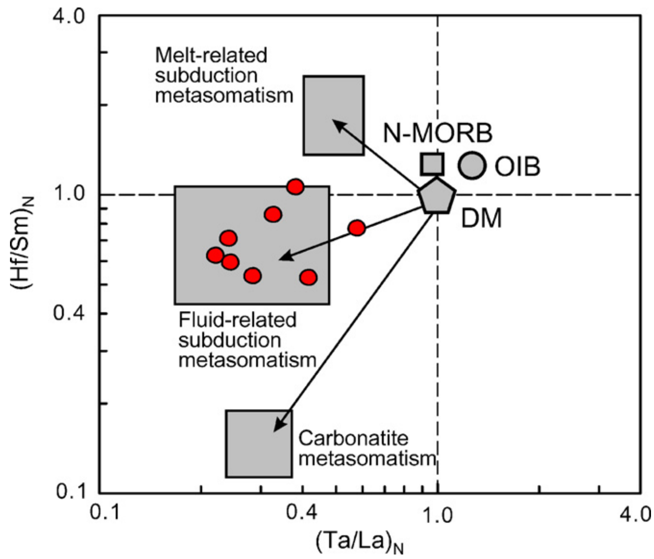

Fig. 9. $(Hf/Sm)_N$ vs. $(Ta/La)_N$ plot (after La Flèche et al., 1998) showing the characteristic depletion of Ta and Hf relative to La and Sm, respectively, for volcanic arc basalts generated from a mantle source metasomatized by subduction-related processes. It suggests that the Pingshui basaltic rocks were likely derived from a mantle source metasomatized by subduction-related fluids.

The Zhangcun rocks are high in silica (SiO_2 mostly >69%), yet low in MgO (0.35–1.2%), comparable to the experimental melts. All samples have a nearly constant Al_2O_3 content of 14–15% over the whole SiO_2 range, in contrast to the Beiwu rocks that show a decrease in Al_2O_3 with increasing SiO_2. Moreover, the Zhangcun rocks have relatively consistent REE and trace element abundances and patterns (Fig. 7c and f). All these geochemical features, in combination with their indistinguishable Nd and Hf isotopic compositions from the older Pingshui and Beiwu rocks, indicate remelting of a juvenile basaltic to andesitic arc crust (similar in comparison to the Pingshui and Beiwu rocks) at low pressure, similar to the silicic rocks in the Izu-Bonin and Tonga-Kermadec arcs (Tamura and Tasumi, 2002; Leat et al., 2007).

5.2. Tectonic implications

The timing of the Sibao orogeny and the final amalgamation between the Yangtze and Cathaysia Blocks is controversial, with two major competing viewpoints, i.e., late Mesoproterozoic to early Neoproterozoic (ca. 1.1–0.9 Ga) (e.g., Z.X. Li et al., 1995, 2002, 2007, 2008; Greentree et al., 2006; X.H. Li et al., 2006a; Ye et al., 2007; W.X. Li et al., 2008a) vs. middle Neoproterozoic (ca. 0.86–0.80 Ga or younger) (e.g., Li, 1999; Zhao and Cawood, 1999; Zhou et al., 2002, 2004; X.L. Wang et al., 2004, 2006, 2007, 2008; Wu et al., 2006; Zheng et al., 2007). Our present study demonstrates that the Shuangxiwu volcanic rocks, as well as the associated ca. 0.91 Ga syntectonic tonalite and granodiorite intrusions (Ye et al., 2007), are typical of arc magmatism along the active southeastern continental margin of the Yangtze Block (Fig. 12a and b). The oldest known arc magmatism here is represented by the ca. 970 Ma basaltic rocks of the Pingshui Formation (Sm–Nd internal isochron age of 978 ± 44 Ma, Zhang et al., 1990; LA-ICPMS Pb/Pb zircon age of 965 ± 12 Ma, Chen et al., 2009). Considering that metamorphism of the Tianli Schists, which are considered part of the SW-extension of the Shuangxiwu arc (marked as "9" and "8", respectively, in Fig. 1), started as early as 1042 ± 7 Ma (Z.X. Li et al., 2007), and that the NE Jiangxi ophiolite formed in the back-arc basin (Fig. 12a and b) at ca. 1.0 Ga (Chen et al., 1991), the initiation age of the Shuangxiwu arc likely occurred no later than 1.0 Ga (Fig. 12a).

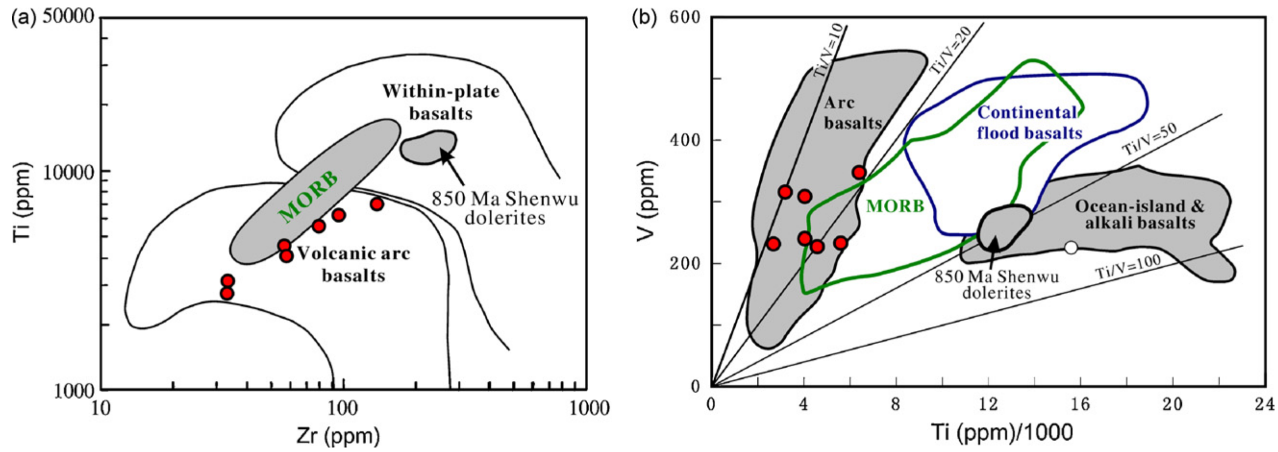

Fig. 10. (a) Ti vs. Zr discrimination diagram of Pearce (1982), and (b) V vs. Ti discrimination diagram of Shervais (1982) for the Pingshui basaltic rocks. The fields of arc basalts, MORB, continental flood basalts, and ocean-island and alkali basalts were drawn by Rollinson (1993) according to Shervais (1982). Data of the ca. 850 Ma Shenwu dolerites are from X.H. Li et al. (2008).

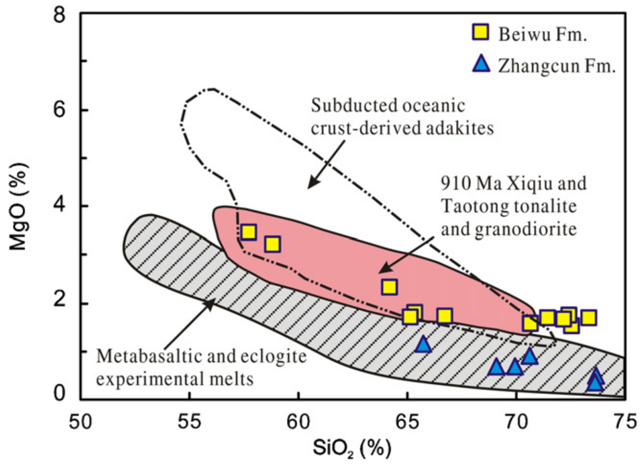

Fig. 11. MgO vs. SiO_2 for the Baiwu and Zhangcun volcanic rocks. The fields of metabasaltic and eclogite experimental melts are after a compilation by Q. Wang et al. (2006), and the fields of the ca. 910 Ma Xiqiu-Taohong tonalite and granodiorite are after Ye et al. (2007).

The youngest known arc magmatism, the Zhangcun Formation rhyolite, is dated at 891 ± 12 Ma (this study), and can be interpreted as the maximum age for the closure of the ocean between the Shuangxiwu arc and the Cathaysia Block. Subduction in the back-arc basin started from at least 968 ± 23 Ma as indicated by the occurrence of the Xiwan adakitic granites (Li and Li, 2003; Fig. 12b), and continued until ca. 880 Ma as indicated by the obduction of the Xiwan ophiolite onto the continent to form the 880 ± 19 Ma obduction-type biotite granites (W.X. Li et al., 2008a; Fig. 12c). This ca. 880 Ma event marks the youngest recorded Neoproterozoic compressive tectonism in the eastern Sibao orogen (Fig. 12c).

The folded Shuangxiwu Group rocks were intruded at 849 ± 7 Ma by the Shenwu dolerites, that show close geochemical affinity to intraplate basalts formed in continental rifts (X.H. Li et al., 2008; Fig. 10). A similar zircon U–Pb age, 857 ± 13 Ma, was reported for the Guandaoshan pluton that intruded the strongly deformed, ≥900 Ma Yanbian Group in the western Sibao orogen (X.H. Li et al., 2003a, 2006a; marked as "2" in Fig. 1). Overlying the Tianli Schists and the Shangxiwu magmatic arc with angular unconformities are the middle Neoproterozoic rift successions of the Nanhua Rift Basin that developed on both the Yangtze and Cathaysia Blocks since ca. 820 Ma (Wang and Li, 2003; Wang et al., 2003; W.X. Li et al., 2005, 2008b), most likely related to ca. 825 Ma mantle plume activities beneath South China (Z.X. Li et al., 1999, 2003; X.C. Wang et al., 2007; Fig. 12d).

The above observations suggest that the transition of the regional tectonic regime from interplate convergence to intracontinental rifting occurred between 880 ± 19 Ma and 849 ± 7 Ma in the eastern Sibao orogen.

In view of the lack of any exposed high-grade metamorphic rocks along the Sibao orogen other than the ca. 900 Ma Xiwan blueschists (location "6" in Fig. 1; Xu et al., 1992; Shu et al., 1993; Charvet et al., 1996a,b; Zhou, 1997) and the ≥1.43 Ga Baoban complex in Hainan Island (marked as "12" in Fig. 1; Z.X. Li et al., 2002), the final docking between the Cathaysia and Yangtze blocks, particularly along the eastern Sibao orogen, was unlikely a collisional one. Such an intercontinental "soft docking" might be possible because of plate

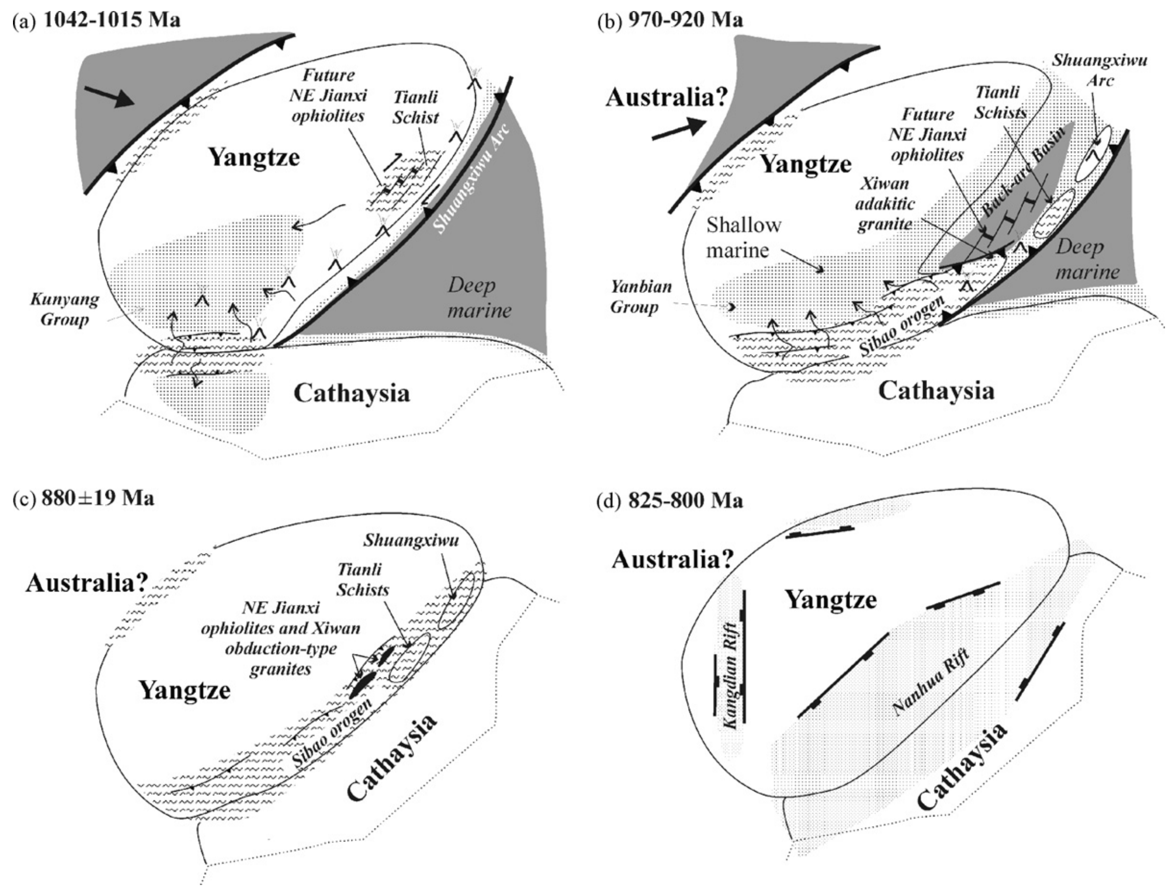

Fig. 12. (a–c) Cartons showing a magmatic arc and back-arc basin system evolving at the active continental margin of the southeastern Yangtze Block during the Sibao orogeny form ca. 1.04 Ga to ca. 0.88 Ga, and (d) subsequent continental rifting at ca. 820–800 Ma (modified after Z.X. Li et al., 2007).

geometry (i.e., regions protected by promontories) and kinematics (e.g., toward the end on an orogeny).

We note that different opinions exist regarding the Neoproterozoic tectonic environments of central and eastern South China, and existing models are constantly being challenged by new results. Rock units particularly relevant to this study are the Lengjiaxi and Sibao groups and their equivalents, that are traditionally thought to form a Mesoproterozoic "basement", as they were unconformably overlain by the middle Neoproterozoic rift successions (e.g., BGMRJX, 1984; BGMRGX, 1985; BGMRHN, 1988). However, recent U–Pb age determinations of detrital zircons from the Lengjiaxi and Sibao groups (X.L. Wang et al., 2007) display two major age peaks of ca. 940–890 Ma and ca. 865–850 Ma, and those authors interpret the rock formations as being formed in a ca. 860–800 Ma foreland basin. We consider such an interpretation inappropriate because the Shuangxiwu Group and the first phase of anorogenic magmatic rocks may be the sources for the above two populations of detrital zircons, respectively (Ye et al., 2007; X.H. Li et al., 2008, and this study). As discussed above, the Shuangxiwu arc appeared to have shut off after ca. 890 Ma and the back-arc basin closed by ca. 880 Ma. No Neoproterozoic metamorphic age younger than that has been reported to suggest the continued presence of an active margin or the closure of any ocean after ca. 880 Ma. The precise tectonic setting for the widespread ca. 850–820 Ma deposits is yet unclear. However, in view of the anorogenic nature of the ca. 850 Ma Shenwu dolorite dykes in eastern South China (X.H. Li et al., 2008) and the ca. 860 Ma Guandaoshan granitoid in western South China (X.H. Li et al., 2003a), and the occurrence of bimodal volcanic rocks in some of those successions (our unpublished results), we tentatively suggest that these rocks may represent an early phase of rifting as speculated by Z.X. Li et al. (2003, 2008).

X.L. Wang et al. (2008) also reported U–Pb zircon ages for two volcanic units in the Shuangqiaoshan Group in northern Jiangxi (regions surrounding "6" and "7" in Fig. 1). Although the authors assigned a major age population of ca. 0.88 Ga as the depositional age of the Shuangqiaoshan Group, a younger age population of ca. 0.77 Ga is also present in the two dated samples, indicating that the Shuangqiaoshan Group could be as young as <0.77 Ga. Those ca. 0.88 Ga zircons characteristically have high εHf(T) values varying from 3.3 to 18.8 (mostly between 8 and 15), very similar to those of the volcanic and intrusive rocks from the Shuangxiwu arc. It is highly likely that those 0.88 Ga zircons with such high εHf(T) values were derived from erosion of the Shuangxiwu magmatic arc during the middle Neoproterozoic. In addition, some ca. 0.82 Ga peraluminous granites from eastern Yangtze Block also contain ca. 0.88–0.91 Ga xenocryst zircons (X.H. Li et al., 2003b; Wu et al., 2006). It is thus likely that a greater magmatic arc with voluminous ca. 0.9 Ga silicic igneous rocks existed along the southeastern margin of the Yangtze Block, and acted as one of the major provenances for the sediments filling the middle Neoproterozoic basins.

6. Conclusions

(1) New SHRIMP U–Pb zircon ages indicate that the Beiwu and Zhangcun volcanic rocks from the middle and uppermost Shuangxiwu Group were formed at 926 ± 15 Ma and 891 ± 12 Ma, respectively. In combination with previously published Sm–Nd and zircon Pb/Pb ages for the Pingshui volcanics, the ages for the Shuangxiwu Group volcanic rocks are constrained to be between ca. 970 Ma and ca. 890 Ma.

(2) Geochemical and Nd–Hf isotopic results suggest that the Pingshui volcanic rocks are typical high-Al basaltic to andesitic rocks generated from partial melting of a mantle wedge matasomatized by subduction-related fluids. The Beiwu andesitic to rhyolitic rocks share isotopic similarities with the nearby, coeval tonalites and granodiorites formed by crystal fractionation of basaltic rocks. The Zhangcun felsic volcanic rocks are likely remelting products of juvenile mafic to intermediate arc rocks. Overall, the Shuangxiwu igneous rocks constitute a typical calc-alkaline arc assemblage formed at the active continental margin of the southeastern Yangtze Block during the earliest Neoproterozoic.

(3) The tectonic transition from plate convergence between the Yangtze and Cathaysia Blocks (the Sibao orogeny) to intracontinental rifting likely occurred at some time between 890 and 850 Ma. The final amalgamation between the Yangtze and Cathaysia blocks, possibly resulting from a "soft docking", likely took place at or soon after ca. 880 Ma, marking the end of the Sibao orogeny. Later, the Shuangxiwu magmatic arc became one of the major sedimentary source regions for middle Neoproterozoic sedimentary basins in South China.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.precamres.2009.07.004.

References

Barth, A.P., Wooden, J.L., Tosdal, R.M., Morrison, J., 1995. Crustal contamination in the petrogenesis of a calc-alkalic rock series: Josephine Mountain intrusion, California. Geol. Soc. Am. Bull. 107, 201–212.

BGMRGX (Bureau of Geology Mineral Resources of Guangxi Province), 1985. Regional Geology of Guangxi Autonomous Region. Geological Publishing House, Beijing, 853 pp. (in Chinese with English abstract).

BGMRHN (Bureau of Geology Mineral Resources of Hunan Province), 1988. Regional Geology of Hunan Province. Geological Publishing House, Beijing, 718 pp. (in Chinese with English Abstract).

BGMRJX (Bureau of Geology Mineral Resources of Jiangxi Province), 1984. Regional Geology of Jiangxi Province. Geological Publishing House, Beijing, 921 pp. (in Chinese with English abstract).

BGMRZJ (Bureau of Geology Mineral Resources of Zhejing Province), 1989. Regional geology of Zhejiang Province. Geological Publishing House, Beijing, 688 pp. (in Chinese with English summary).

Black, L.P., Kamo, S.L., Allen, C.M., Davis, D.W., Aleinikoff, J.N., Valley, J.W., Mundil, R., Campbel, I.H., Korsch, R.J., Williams, I.S., Foudoulis, Chris, 2004. Improved $^{206}Pb/^{238}U$ microprobe geochronology by the monitoring of a trace-element-related matrix effect; SHRIMP, ID-TIMS, ELA-ICP-MS and oxygen isotope documentation for a series of zircon standards. Chem. Geol. 205, 115–140.

Charvet, J., Shu, L., Shi, Y., Guo, L., Faure, M., 1996a. The building of south China: collision of Yangzi and Cathaysia blocks, problems and tentative answers. J. SE Asian Earth Sci. 13, 223–235.

Chen, J., Foland, K.A., Xing, F., Xu, X., Zhou, T., 1991. Magmatism along the south-eastern margin of the Yangtze block: Precambrian collision of the Yangtze and Cathysia blocks of China. Geology 19, 815–818.

Chen, Z.H., Xing, G.F., Guo, K.Y., Dong, Y.G., Chen, R., Zeng, Y., Li, L.M., He, Z.Y., Zhao, L., 2009. Petrogenesis of the Pingshui keratophyre from Zhejiang: Zircon U–Pb age and Hf isotope constraints. Chin. Sci. Bull. 54, 610–617 (in Chinese).

Cheng, H., 1993. Geochemistry of Proterozoic island-arc volcanic rocks in Northwest Zhejiang. Geochimica 22, 18–27 (in Chinese with English Abstract).

Charvet, J., Shu, L., Shi, Y., Guo, L., Faure, M., 1996b. The building of south China: collision of Yangtze and Cathaysia blocks, problems and tentative answers. J. SE Asian Earth Sci. 13, 223–235.

Crawford, A.J., Falloon, T.J., Eggins, S., 1987. The origin of island arc high-alumina basalts. Contrib. Mineral. Petrol. 97, 417–430.

Cumming, G.L., Richards, J.R., 1975. Ore lead isotope ratios in a continuously changing Earth. Earth Planet. Sci. Lett. 28, 155–171.

Defant, M.J., Drummond, M.S., 1993. Mount St. Helens: potential example of the partial melting of the subducted lithosphere in a volcanic arc. Geology 21, 547–550.
Drummond, M.S., Defant, M.J., 1990. A modal for trondhjemite–tonalite–dacite genesis and crustal growth via slab melting: Archaean to modern comparisions. J. Geophys. Res. 95, 21503–21521.
Ellam, R.M., Cox, K.G., 1991. An interpretation of Karoo picrite basalts in terms of interaction between asthenospheric magmas and the mantle lithosphere. Earth Planet. Sci. Lett. 105, 330–342.
Gao, S., Ling, W.L., Qiu, Y.M., Lian, Z., Hartmann, G., Simon, K., 1999. Contrasting geochemical and Sm–Nd isotopic compositions of Archean metasediments from the Kongling high-grade terrain of the Yangtze craton: evidence for Cratonic evolution and redistribution of REE during crustal anatexis. Geochim. Cosmochim. Acta 63, 2071–2088.
Gibson, S.A., Kirkpatrick, R.J., Emmerman, R., Schmincke, P.H., Pritchard, G., Okay, P.J., Horpe, R.S., Marriner, G.F., 1982. The trace element composition of the lavas and dykes from a 3 km vertical section through a lava pile of Eastern Iceland. J. Geophys. Res. 87, 6532–6546.
Greentree, M.R., Li, Z.X., 2008. The oldest known rocks in south western China: SHRIMP U–Pb magmatic crystallisation age and detrital provenance analysis of the Paleoproterozoic Dahongshan Group. J. Asia Earth Sci. 33, 289–302.
Greentree, M.R., Li, Z.X., Li, X.H., Wu, H., 2006. Late Mesoproterozoic to earliest Neoproterozoic basin record of the Sibao orogenesis in western South China and relationship to the assembly of Rodinia. Precambrian Res. 151, 79–100.
Hawkesworth, C.J., Lightfoot, P.C., Fedorenko, V.A., Blake, S., Naldrett, A.J., Doherty, W., Gorbachev, N.S., 1995. Magma differentiation and mineralisation in the Siberian continental flood basalts. Lithos 34, 61–88.
Haynes, S.J., 1988. Structural reconnaissance of the Jiangnan geoanticline: a suspected terrane of compressional tectonic character. In: Howell, D.G., Wiley, T.J. (Eds.), Proc. 4th Int. Tectonostratigraphic Terrane Conf. U.S.G.S. Menlo Park, pp. 31–33.
Hsü, K.J., Sun, S., Li, J.L., Chen, H.H., Peng, H.P., Şengör, A.M.C., 1988. Mesozoic overthrust tectonics in South China. Geology 16, 418–421.
Hsü, K.J., Li, J.L., Chen, H.H., Wang, Q.C., Sun, S., Şengör, A.M.C., 1990. Tectonics of South China: key to understanding West-Pacific geology. Tectonophysics 183, 9–39.
Hu, A., Zhu, B., Mao, C.X., Zhu, N., Hunang, R., 1991. Geochronology of the Dahongshan Group. Chin. J. Geochem. 10, 195–203.
La Flèche, M.R., Camire, G., Jenner, G.A., 1998. Geochemistry of post-Acadian, Carboniferous continental intraplate basalts from the Maritimes Basin, Magdalen islands, Quebec, Canada. Chem. Geol. 148, 115–136.
Leat, P.T., Larter, R.D., Millar, I.L., 2007. Silicic magmas of Protector Shoal, South Sandwich arc: indicators of generation of primitive continental crust in an island arc. Geol. Mag. 144, 179–190.
Li, W.X., Li, X.H., 2003. Adakitic granites within the NE Jiangxi ophiolites, South China: geochemical and Nd isotopic evidence. Precambrian Res. 122, 29–44.
Li, W.X., Li, X.H., Li, Z.X., 2005. Neoproterozoic bimodal magmatism in the Cathaysia Block of South China and its tectonic significance. Precambrian Res. 136, 51–66.
Li, W.X., Li, X.H., Li, Z.X., Lou, F.S., 2008a. Obduction-type granites within the NE Jiangxi Ophiolite: implications for the final amalgamation between the Yangtze and Cathaysia Blocks. Gondwana Res. 13, 288–301.
Li, W.X., Li, X.H., Li, Z.X., 2008b. Middle Neoproterozoic syn-rifting volcanic rocks in Guangfeng, South China: petrogenesis and tectonic significance. Geol. Mag. 145, 475–489.
Li, X.H., Zhou, G., Zhao, J., Fanning, C.M., Compston, W., 1994. SHRIMP ion microprobe zircon U–Pb age of the NE Jiangxi ophiolite and its tectonic implications. Geochimica 23, 125–131 (in Chinese with English abstract).
Li, X.H., McCulloch, M.T., 1996. Secular variations in the Nd isotopic composition of Late Proterozoic sediments from the southern margin of the Yangtze Block: evidence for a Proterozoic continental collision in SE China. Precambrian Res. 76, 67–76.
Li, X.H., 1997. Timing of the Cathaysia Block Formation: constraints from SHRIMP U–Pb Zircon Geochronology. Episodes 30, 188–192.
Li, X.H., 1999. U–Pb Zircon ages of granites from the southern margin of the Yangtze Block: timing of the Neoproterozoic Jinning Orogeny in SE China and implications for Rodinia assembly. Precambrian Res. 97, 43–57.
Li, X.H., Sun, M., Wei, G.J., Liu, Y., Lee, C.Y., Malpas, J.G., 2000. Geochemical and Sm–Nd isotopic study of amphibolites in the Cathaysia Block, SE China: evidence for extremely depleted mantle in the Paleoproterozoic. Precambrian Res. 102, 251–262.
Li, X.H., Li, Z.X., Zhou, H.W., Liu, Y., Liang, X., Li, W., 2003a. SHRIMP U–Pb zircon age, geochemistry and Nd isotope of the Guandaoshan pluton in SW Sichuan: Petrogenesis and tectonic significance. Sci. China Ser. D 46 (Suppl.), 73–83.
Li, X.H., Li, Z.X., Ge, W., Zhou, H., Li, W., Liu, Y., Wingate, M.T.D., 2003b. Neoproterozoic granitoids in South China: crustal melting above a mantle plume at ca. 825 Ma? Precambrian Res. 122, 45–83.
Li, X.H., Liu, D.Y., Sun, M., Li, W.X., Liang, X.R., Liu, Y., 2004. Precise Sm–Nd and U–Pb isotopic dating of the super-giant Shizhuyuan polymetallic deposit and its host granite, Southeast China. Geol. Mag. 141, 225–231.
Li, X.H., Qi, C.S., Liu, Y., Liang, X.R., Tu, X.L., Xie, L.W., Yang, Y.H., 2005. Petrogenesis of the Neoproterozoic bimodal volcanic rocks along the western margin of the Yangtze Block: new constraints from Hf isotopes and Fe/Mn ratios. Chin. Sci. Bull. 50, 2481–2486.
Li, X.H., Li, Z.X., Sinclair, J.A., Li, W.X., Carter, G., 2006a. Revisiting the "Yanbian Terrane": implications for Neoproterozoic tectonic evolution of the western Yangtze Block, South China. Precambrian Res. 151, 14–30.
Li, X.H., Li, Z.X., Li, W.X., Wang, Y.J., 2006b. Initiation of the Indosinian Orogeny in South China: evidence for a Permian magmatic arc on the Hainan Island. J. Geol. 114, 341–353.
Li, X.H., Liu, Y., Yang, Y.H., Chen, F.K., Tu, X.L., Qi, C.S., 2007. Rapid separation of Lu–Hf and Sm–Nd from a single rock dissolution and precise measurement of Hf–Nd isotopic ratios for national rock standards. Acta Petrol. Sinica 23, 221–226 (in Chinese with English abstract).
Li, X.H., Li, W.X., Li, Z.X., Liu, Y., 2008. 850-790 Ma bimodal volcanic and intrusive rocks in northern Zhejiang, South China: a major episode of continental rift magmatism during the breakup of Rodinia. Lithos 102, 341–357.
Li, Z.X., Zhang, L.H., McApowell, C., 1995. South China in Rodinia: part of the missing link between Australia-East Antarctica and Laurentia? Geology 23, 407–410.
Li, Z.X., Li, X.H., Kinny, P.D., Wang, J., 1999. The breakup of Rodinia: did it start with a mantle plume beneath South China? Earth Planet. Sci. Lett. 173, 171–181.
Li, Z.X., Li, X.H., Zhou, H.W., Kinny, P.D., 2002. Grenvillian continental collision in south China: new SHRIMP U–Pb zircon results and implications for the configuration of Rodinia. Geology 30, 163–166.
Li, Z.X., Li, X.H., 2007. Formation of the 1300 km-wide intra-continental orogen and post-orogenic magmatic province in Mesozoic South China: a flat-slab subduction model. Geology 35, 179–182.
Li, Z.X., Li, X.H., Kinny, P.D., Wang, J., Zhang, S., Zhou, H., 2003. Geochronology of Neoproterozoic syn-rift magmatism in the Yangtze Craton, South China and correlations with other continents: evidence for a mantle superplume that broke up Rodinia. Precambrian Res. 122, 85–109.
Li, Z.X., Wartho, J.A., Occhipinti, S., Zhang, C.L., Li, X.H., Wang, J., Bao, C.M., 2007. Early history of the eastern Sibao Orogen (South China) during the assembly of Rodinia: new mica $^{40}Ar/^{39}Ar$ dating and SHRIMP U–Pb detrital zircon provenance constraints. Precambrian Res. 159, 79–94.
Li, Z.X., Bogdanova, S.V., Collins, A.S., Davidson, A., De Waele, B., Ernst, R.E., Fitzsimons, I.C.W., Fuck, R.A., Gladkochub, D.P., Jacobs, J., Karlstrom, K.E., Lu, S., Natapov, L.M., Pease, V., Pisarevsky, S.A., Thrane, K., Vernikovsky, V., 2008. Assembly, configuration, and break-up history of Rodinia: a synthesis. Precambrian Res. 160, 179–210.
McCulloch, M.T., Gamble, J.A., 1991. Geochemical and geodynamical constraints on subduction zone magmatism. Earth Planet. Sci., Lett. 102, 358–374.
Münker, C., Wörner, G., Yogodzinski, G.M., Churikova, T.G., 2004. Behaviour of high field strength elements in subduction zones: constraints from Kamtchatka–Aleutian arc lavas. Earth Planet. Sci. Lett. 224, 275–293.
Nelson, D.R., 1997. Compilation of SHRIMP U–Pb zircon geochronology data, 1996. In: Geological Survey of Western Australia Record 1997/2. Geological Survey of Western Australia, Perth, 189 pp.
Nowell, G.M., Kempton, P.D., Noble, S.R., Fitton, J.G., Saunders, A.D., Mahoney, J.J., Taylor, R.N., 1998. High precision Hf isotope measurements of MORB and OIB by thermal ionisation mass spectrometry: insights into the depleted mantle. Chem. Geol. 149, 211–233.
Pearce, J.A., 1982. Trace element characteristics of lavas from destructive plate boundaries. In: Thorpe, R.S. (Ed.), Andesites. Wiley, New York, pp. 525–548.
Qiu, Y.M., Gao, S., McNaughton, N.J., Groves, D.L., Ling, W.L., 2000. First evidence of >3.2 Ga continental crust in the Yangtze craton of South China and its implications for Archean crustal evolution and Phanerozoic tectonics. Geology 28, 11–14.
Rapp, R.P., Watson, E.B., 1995. Dehydration melting of metabasalt at 8–32 kbar: implications for continental growth and crust-mantle recycling. J. Petrol. 36, 891–931.
Rollinson, H.R., 1993. Using Geochemical Data: Evaluation, Presentation, Interpretation. Longman Geochemistry Society, London, 352 pp.
Rushmer, T., 1991. Partial melting of two amphibolites: contrasting experimental results under fluid-absent conditions. Contrib. Mineral. Petrol. 107, 41–59.
Schiano, P., Clocchiatti, R., Boivin, P., Medard, E., 2004. The nature of melt inclusions inside minerals in an ultramafic cumulate from Adak volcanic center, aleutian arc: implications for the origin of high-Al basalts. Chem. Geol. 203, 169–179.
Shervais, J.W., 1982. Ti–V plots and the petrogenesis of modern and ophiolitic lavas. Earth Planet. Sci. Lett. 59, 101–118.
Shu, L., Zhou, G., Shi, Y., Yin, J., 1993. Study of high-pressure blueschists in eastern Jiangnan Orogenic Belt and their metamorphic age. Chin. Sci. Bull. 38, 1879–1882 (in Chinese with English abstract).
Singer, B.S., Myers, J.D., Frost, C.D., 1992. Mid-Pleistocene lavas from the Seguam volcanic center, central Aleutian arc: closed-system fractional crystallization of a basalt to rhyodacite eruptive suite. Contrib. Mineral. Petrol. 110, 87–112.
Sisson, T.W., Grove, T.L., 1993. Temperatures and H_2O contents of low-MgO high-alumina basalts. Contrib. Mineral. Petrol. 113, 167–184.
Smithies, R.H., 2000. The Archean tonalite-trondhiemite-granodiorite (TTG) series is not an analogue of Cenozoic adakite. Earth Planet. Sci. Lett. 182, 115–125.
Sun, S.S., McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalt: implications for mantle composition and processes. In: Sanders, A.D., Norry, M.J. (Eds.), Magmatism in the Ocean Basins. Geol. Soc. Spec. Pub., vol. 42, pp. 528–548.
Tamura, Y., Tasumi, Y., 2002. Remelting of an andesitic crust as a possible origin for rhyolitic magma in oceanic arcs: an example from the Izu-Bonin arc. J. Petrol. 43, 1029–1047.
Tatsumi, Y., Eggins, S.M., 1995. Subduction Zone Magmatism. Blackwell Science, Cambridge, 211 pp.
Vervoort, J., Patchett, P.J., Blichert-Toft, J., Albarède, F., 1999. Relationships between Lu–Hf and Sm–Nd isotopic systems in the global sedimentary system. Earth Planet. Sci. Lett. 168, 79–99.
Wang, J., Li, Z.X., 2003. History of Neoproterozoic rift basins in South China: implications for Rodinia break-up. Precambrian Res. 122, 141–158.

Wang, J., Li, X.H., Duan, T.Z., Liu, D.Y., Song, B., Li, Z.X., Gao, Y.H., 2003. Zircon SHRIMP U–Pb dating for the Cangshuipu volcanic rocks and its implications for the lower boundary age of the Nanhua strata in South China. Chi. Sci. Bull. 48, 1663–1669.

Wang, Q., Xu, J.F., Jian, P., Bao, Z.W., Zhao, Z.H., Li, C.Y., Xiong, X.L., Ma, J.L., 2006. Petrogenesis of Adakitic porphyries in an extensional tectonic setting, Dexing, South China: implications for the genesis of porphyry copper mineralization. J. Petrol. 47, 119–144.

Wang, X.C., Li, X.H., Li, W.X., Li, Z.X., 2007. Ca. 825 Ma komatiitic basalts in South China: first evidence for >1500 °C mantle melts by a Rodinian mantle plume. Geology 35, 1103–1106.

Wang, X.C., Li, X.H., Li, W.X., Li, Z.X., Liu, Y., Yang, Y.H., Liang, X.R., Tu, X.L., 2008. The Bikou basalts in northwestern Yangtze Block, South China: remnants of 820–810 Ma continental flood basalts? GSA Bull. 120, 1478–1492.

Wang, X.L., Zhou, J.C., Qiu, J.S., Gao, J.F., 2004. Geochemistry of the Meso- to Neoproterozoic basic-acid rocks from Hunan Province, South China: implications for the evolution of the western Jiangnan orogen. Precambrian Res. 135, 79–103.

Wang, X.L., Zhou, J.C., Qiu, J.S., Zhang, W.L., Liu, X.M., Zhang, G.L., 2006. LA-ICP-MS U–Pb zircon geochronology of the Neoproterozoic igneous rocks from Northern Guangxi, South China: implications for tectonic evolution. Precambrian Res. 145, 111–130.

Wang, X.L., Zhou, J.C., Griffin, W.L., Wang, R.C., Qiu, J.S., O'Reilly, S.Y., Xu, X.S., Liu, X.M., Zhang, G.L., 2007. Detrital zircon geochronology of Precambrian basement sequences in the Jiangnan orogen: dating the assembly of the Yangtze and Cathaysia blocks. Precambrian Res. 159, 117–131.

Wang, X.L., Zhao, G., Zhou, J.C., Liu, Y., Hu, J., 2008. Geochronology and Hf isotopes of zircon from volcanic rocks of the Shuangqiaoshan Group, South China: implications for the Neoproterozoic tectonic evolution of the eastern Jiangnan orogen. Gond. Res. 14, 355–367.

Winchester, J.A., Floyd, P.A., 1976. Geochemical magma type discrimination: application to altered and metamorphosed basic igneous rocks. Earth Planet. Sci. Lett. 28, 459–469.

Wood, D.A., Joron, J.L., Treuil, M., 1979. A re-appraisal of the use of trace elements to classify and discriminate between magma series erupted in different tectonic settings. Earth Planet. Sci. Lett. 45, 326–336.

Wu, R.X., Zheng, Y.F., Wu, Y.B., Zhao, Z.F., Zhang, S.B., Liu, X.M., Wu, F.Y., 2006. Reworking of juvenile crust: element and isotope evidence from Neoproterozoic granodiorite in South China. Precambrian Res. 146, 179–212.

Xu, B., Guo, L., Shi, Y., 1992. Proterozoic Terranes and Multiphase Collision Orogens in Anhui-Zhejiang-Jiangxi Ares. Geological Publishing House, Beijing, 112 pp.

Ye, M.F., Li, X.H., Li, W.X., Liu, Y., Li, Z.X., 2007. SHRIMP zircon U–Pb geochronological and whole-rock geochemical evidence for an early Neoproterozoic Sibaoan magmatic arc along the southeastern margin of the Yangtze Block. Gond. Res. 12, 144–156.

Zhang, B.T., Ling, H.F., Shen, W.Z., Liu, J.S., Yang, J.D., Tao, X.C., 1990. Sm–Nd isochronic age of spilite-keratophyre of Shuangxiwu Group in Xiqiu, Shaoxing, Zhejiang Province. J. Nanjing Univ. (Earth Science) 2, 9–14 (in Chinese with English Abstract).

Zhang, Z.J., Badal, B., Li, Y.K., Chen, Y., Yang, L.P., Teng, J.W., 2005. Crust–upper mantle seismic velocity structure across Southeastern China. Tectonophysics 395, 137–157.

Zhao, G.C., Cawood, P.A., 1999. Tectonothermal evolution of the Mayuan assemblage in the Cathaysia Block: implications for Neoproterozoic collision-related assembly of the South China craton. Am. J. Sci. 299, 309–339.

Zheng, Y.F., Zhang, S.B., Zhao, Z.F., Wu, Y.B., Li, X.H., Li, Z.X., Wu, F.Y., 2007. Contrasting zircon Hf and O isotopes in the two episodes of Neoproterozoic granitoids in South China: implications for growth and reworking of continental crust. Lithos 96, 127–150.

Zhou, G.Q., 1997. Jadeitic rocks from high-pressure metamorphic zone of NE Jiangxi province: formation and preservation condition. Sci. China Ser. D 27, 45–51 (in Chinese with English abstract).

Zhou, J.C., Wang, X.L., Qiu, J.S., Gao, J.F., 2004. Geochemistry of Meso- and Neoproterozoic mafic-ultramafic rocks from northern Guangxi, China: arc or plume magmatism? Geochem. J. 38, 139–152.

Zhou, M.F., Yan, D.P., Kennedy, A.K., Li, Y., Ding, J., 2002. SHRIMP U–Pb zircon geochronological and geochemical evidence for Neoproterozoic arc-magmatism along the western margin of the Yangtze Block, South China. Earth Planet. Sci. Lett. 196, 51–67.

Zhou, M.F., Ma, Y., Yan, D.P., Xia, X., Zhao, J.H., Sun, M., 2006. The Yanbian Terrane (Southern Sichuan Province, SW China): a Neoproterozoic arc assemblage in the western margin of the Yangtze Block. Precambrian Res. 144, 19–38.

ZPGST (Zhejiang Provincial Geological Survey Team), 1975. 1:200,000 Geological Map of Zhuji.